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KINETICS OF EXTENDED AERATION

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Presented by

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at

Thirteenth Southern Municipal and

Industrial Waste Conference

Duke University

Durham, North Carolina

April 16 and 17, 1964

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Page 11 - Figure 2 - Substitute enclosed Figure.

Page 13 - Line 9 - Change "0.10 to 0.15" to read "0.010 to 0.015".

Introduction

The use of extended aeration activated sludge systems has had a remarkably rapid increase. These systems in a few years have gained general acceptance by environmental engineering consultants and regulatory agencies as a preferred means of treating small waste discharges requiring secondary treatment effluent quality. All types of activated sludge plants have been adapted to extended aeration operation. Heterogeneous systems with batch loading schedules are often used for the treatment of dairy waste. Modified conventional systems and completely mixed systems have been most popular for treating small industrial and housing development wastes.

Several features of this type of activated sludge process have contributed to its popularity. Not the least of these is the low rate of sludge accumulation within the system. In many extended aeration plants the solids accumulation is handled by natural discharge of organic "ash" out the effluent. This phenomenon of low solids accumulation eliminates the need for anaerobic digesters. Also, this process operates without primary sedimentation. These two features contribute greatly to the comparatively low cost of construction of extended aeration plants.

Unfortunately, too often extended aeration plants have not shown the performance for which they were designed. Whether this difficulty is the result of improper engineering or poor operation, the consequence is the same. Regulatory agencies require more safe-guards in the design in order to fulfill their obligation to protect the public's interest. One consequence has been that various state regulatory agencies require sludge holding tanks. Another consequence

is the requirement of sand filters to polish the effluents when these would not be required for conventional activated sludge plants.

It is not the purpose of this paper to comment on the creditability of an agency requirements. Rather it is to present the current kinetics theory of the extended aeration activated sludge process. It is felt that a better understanding of the process will foster better design and operation. It is only through an increased understanding of the process by all those concerned that regulatory agencies will become more flexible in their requirements.

Description of Activated Sludge

In considering the theory of operation of an extended aeration process, it is appropriate to start with the basic nature of the process. I am sure you are all aware that extended aeration is a modification of the activated sludge process. But what then is an activated sludge process and what makes it activated?

An activated sludge process is one in which those organisms which will flocculate are selectively returned to the aerator. They are able to incorporate in their floc matrix essentially all the organisms grown plus any suspended solids in the influent. During aeration the active organisms metabolize the available food. On sedimentation, they are removed from the solution yielding a clear, low organic content effluent. The return of the hungry organisms to be mixed with the influent waste is the activation of this process.

The extended aeration system is a modification of the activated sludge system in which, as the name implies, the period of aeration has been extended beyond the normal by a significant amount.

The kinetics for both systems are quite similar so that, unless otherwise stated, the material given here will apply generally to activated sludge processes.

Biological Nature of the Process

It is most important for the engineers and operators to understand the significance implicit in the fact that these are biological processes. Any biological family, whether it be bacteria, protozoa, or algae, have certain environmental conditions in which they thrive. At the same time, there are other conditions in their environment which must be met for their survival. It is important that those working with activated sludge have some feeling for its optimum and limiting environmental conditions. I will attempt to present some biological relationships which are defined by the environmental parameters.

Normally, the most predominant organisms in activated sludge are bacteria. Their growth is the result of the metabolism of organic waste. The total synthesis, or development of new protoplasm in the sludge, which will occur is a function of the food removed.

$$\text{Synthesis} = f\ [\text{Food Removed}] \qquad (1)$$

The rate at which the sludge is synthesized is, however, a function of the food concentration in the reactor or aeration tank.

$$\text{Synthesis Rate} = f\ [\text{Food Concentration in Reactor Tank}] \qquad (2)$$

The sludge in the system does not continue to accumulate to astronomical amounts as implied by the equation (1). There are several factors which tend to limit the bacteria population. Some

of these factors which will effect the accumulation of bacteria, even in a treatment system having an optimum environment, will be mentioned here.

(1) Protozoa, rotifers, curstaceans and other animal forms develop in these waste treatment systems. These preditors prey on the bacteria which are their major food supply.

(2) The food concentration in the reactor decreases with increased active micobial sludge carried in the reactor. Under these circumstances, according to equation (2), the rate of bacterial synthesis would also decrease.

(3) In some cases, if no natural or artificial wasting occurs, space may be the limiting factor for bacterial growth.

(4) In all cases, auto-digestion and autolysis, preceding concurrently with the synthesis reaction tend to reduce the sludge mass. Both of these biological reactions can be considered jointly to be endogenous metabolism.

This process does not result in the total destruction of the organisms undergoing endogenous metabolism. A portion of the cell in the sludge mass is not readily degraded by the culture. The remaining material, so called "Ash," amounts to about 20 percent of the weight of the bacteria digested.

(5) Finally, sludge wasting will control the bacteria population. This is common practice in activated sludge systems operating with a <u>normal</u> aeration period. Wasting has also been found to be a desirable practice in some extended aeration activated sludge plants.

The organic sludge accumulation which occurs as a result of the microbial activity in the activated sludge process can be expressed in a mathematical model as shown in equation (3).

$$\frac{\Delta M}{\Delta t} = A = \frac{C\ F_R}{V} - k\ M_a + j\ k\ M_a - M_e\ Q/V \qquad (3)$$

This equation states that the daily volatile sludge accumulation per volume is the result of the synthesis, $\frac{C\ F_R}{V}$, the endogenous metabolism, $(j - 1)\ k\ M_a$, and loss in the effluent, $(-M_e\ Q/V)$. The sludge in the effluent represents solids wasted by natural and artificial means. In this equation the time period must equal or exceed the detention period of the reactor to be applicable to heterogeneous as well as homogeneous systems. In addition to the accumulation given in these expressions, inorganic as well as organic solids may accumulate in the sludge as a result of suspended material in the influent.

At steady state operation the active mass, on the average, remains constant. Then

$$\frac{\Delta M_a}{\Delta t} = A_a = CL - k\ M_a - M_{ea}\ Q/V = 0 \qquad (4)$$

Since the active mass in the effluent, (M_{ea}) can be expressed as a function of the active mass in the system, then from equation (4):

$$M_a = \frac{CL}{k + \frac{f(M_a)}{T_D\ M_a}} \qquad (5)$$

This is a generalized equation for the active mass in an activated sludge system at steady state operation. Unfortunately the fraction of active mass removed from the system, $\frac{f(M_a)}{M_a}$, is not well defined unless sludge wasting is controlled. It is, however, possible to define the limiting values of active mass carried in a system regardless of the nature of this sludge wasting function. It is readily

apparent from equation (5) that the maximum active mass, for a given process loading, will exist under conditions of no sludge wasting, i.e. $\frac{f(M_a)}{M_a} = 0$. Then

$$M_{a_{max}} = \frac{C}{k} L \tag{6}$$

In contrast, the minimum active mass for a given process loading will occur when the detention time equals the minimum generation time (maximum growth rate) of the organisms. This condition is approached in high rate activated sludge systems. The minimum active mass cannot be maintained in any system which recirculates a substantial portion of the sludge produced, because the increased population will reduce the substrate concentration below that required for maximum log growth. The best example of a minimum active mass system would be an aeration-only system. Under these conditions all the active mass is replaced in the system during a detention period. Then from equation (5) the minimum active mass is given by:

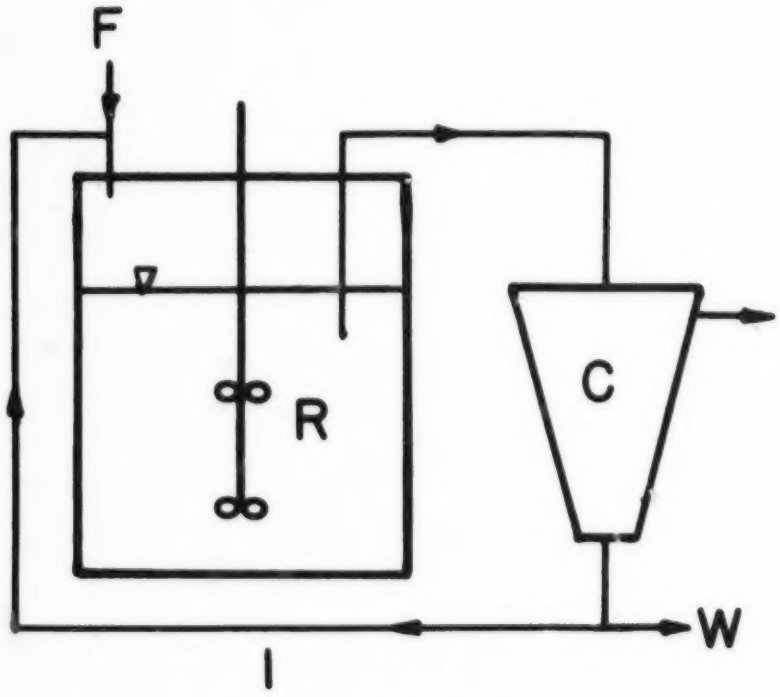
$$M_{a_{min}} = \frac{C\ L}{k + 1/T_D} \tag{7}$$

It should be remembered that biological systems must be supplied certain mineral nutrients in addition to the organic material considered thus far. Since the synthesized cells contain minerals, there must be a sufficient source of mineral nutrients present in the waste to assure maximum BOD removal. The most important minerals, in terms of amounts required, are nitrogen and phosphorous. They account for about 10 percent and 2 percent of the cells by weight, respectively.

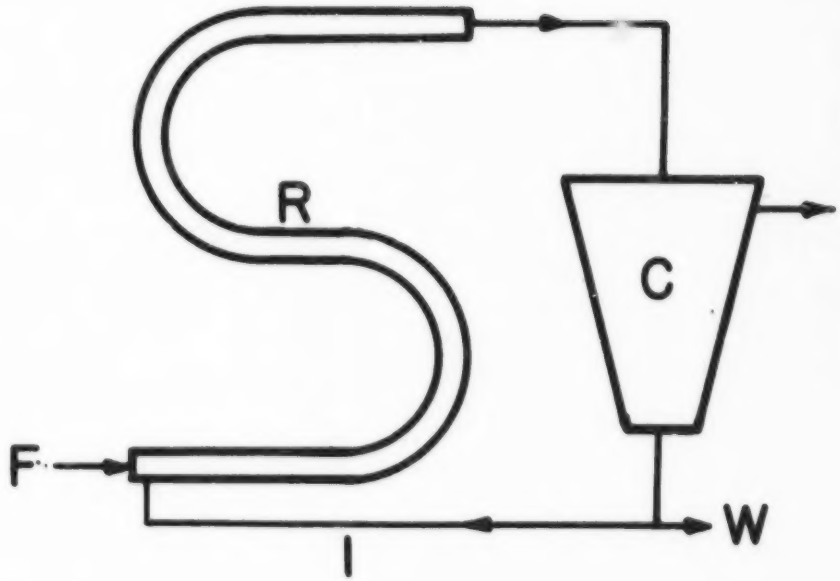
Classification of Activated Sludge Systems

Equation (3) can be used to represent the volatile sludge accumulation rate regardless of the type of activated sludge process. The question then may be asked as to what are the types of activated sludge systems. From a biological point of view, all biological processes for waste treatment are in the group of open systems, i.e. they do not retain all the organisms produced. In addition, they may be classified as to the loading schedule under which they operate. The loading schedule, to a great extent, dictates the organisms' environment. The extremes of the classification are illustrated in Figure 1. The completely mixed system introduces the food (F) together with the recirculated sludge (I) into an aerated reactor (R), which, as the name implies, is completely mixed. This results in a homogeneous environment for the sludge organisms during their entire retention in the reactor. The sludge is then separated from the mixed liquor in a clarifier (C) with the sludge being recirculated (I) or wasted (W) and the treated water going to effluent discharge. In this system, the environment is most conducive to developing set groups of predominant and secondary organisms which remain fairly constant in species and number with time for a given organic loading.

The conventional system is operated similarly to the completely mixed system except a long reactor is used. In the long reactor there is transverse mixing with little longitudinal mixing. In this system there is a heterogeneous environment which changes incrementally with distance through the aeration tank. This heterogeneous reactor could also be represented by a batch fed system wherein the environ-



COMPLETELY MIXED
(HOMOGENOUS)



CONVENTIONAL
(HETEROGENEOUS)

F - FOOD; C - CLARIFIER; R - REACTOR; I - RECIRCULATION; W - WASTE

FIG. 1 - ACTIVATED SLUDGE SYSTEMS

ment changes incrementally with time of reaction. In such a system treating a waste containing a mixture of organic compounds, the substrate concentration and composition change with time of aeration. As a consequence so does the predominant bacterial population, both in species and number.

Activated sludge systems are commonly classified according to their daily sludge accumulation rate. Differences in the sludge accumulation rate of activated sludge processes have given rise to such process modifications as dispersed aeration, bio-absorption, and extended aeration. The sludge accumulation rate can be controlled, regardless of the process loading schedule, by controlling the process loading factor.

Process Loading Factor

The process loading factor is the amount of organic food supplied each day to the viable organisms. This parameter has been referred to by some writers as the food to microorganism ratio ($F_a:M_a'$), where F_a equals food applied and M_a' equals the active mass. Various unit systems have been used to approximate this parameter for field use. None of these, however, have completely described the process loading factor. This difficulty is due in part to our inability at present to measure the true active protoplasm in a treatment system. Perhaps the process loading factor will ultimately be measured as pounds of ultimate biochemical oxygen demand (BOD_L) applied per day to the pounds of active protoplasm in the system.

Activated sludge systems are designed to treat a given quantity of organic waste. The volume and strength of the waste usually

fluctuate widely during the day, but the daily averages remain substantially the same. Therefore, the various modifications of the activated sludge process are accomplished by control of the active sludge by adjustment of the mixed liquor suspended solids.

The effect or process loading factor on sludge synthesis and accumulation is shown in Figure 2. As stated in the sludge accumulation equation (3), the synthesis is a constant percentage of the food removed. On the basis of accumulation factor, a review of published data gives a mean yield coefficient (C) equal to 0.38. This value also represents the maximum sludge accumulation rate which will occur during log growth. To maintain a system at this maximum rate of sludge accumulation, an aeration-only system would be required. If the sludge solids are allowed to increase as a result of a reduction in sludge wasting, the process loading factor decreases. As can be seen from Figure 2, there will be an accompanying reduction in sludge accumulation. This situation follows from equation (3) which shows a reduction in sludge accumulation with increased active mass as a consequence of endogenous metabolism.

The operational range of several modifications of the activated sludge process is given in Figure 2. The ranges are only approximate in that they were computed based upon the published values given in other than active mass units.

If the process loading factor is allowed to decrease, a minimum point of sludge accumulation is reached. At this process loading factor and below, an equilibrium of maximum active mass occurs at which all the accumulation of solids is "Ash". Our work indicates

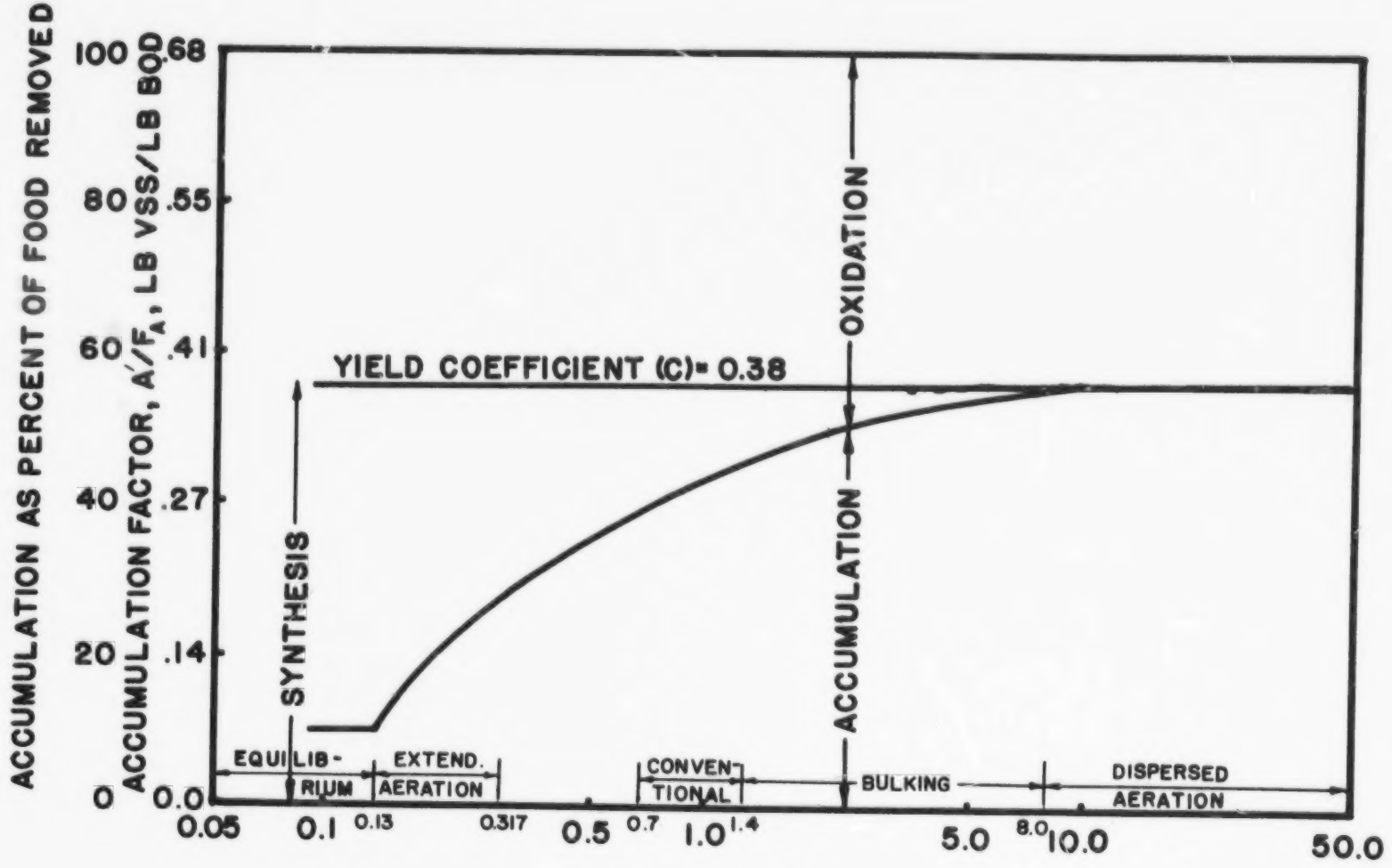


FIG. 2 - SYNTHESIS AND ACCUMULATION

that the minimum accumulation amounts to 10 percent of the food removed on a BOD_L basis. Practically, this equilibrium point can best be reached by extending the period of aeration. Hence, we get extended aeration systems.

The rate of synthesis is a function of the substrate concentration (equation (2)) as well as the number of active organisms. Therefore, the loading schedule as well as the process loading factor will influence the type of activated sludge operation which prevails in a waste treatment plant. The effect of loading schedule is most significant at high process loading factors and decreases to zero at equilibrium operations.

The use of a process loading factor for describing any modification of the activated sludge process is preferable to the often used volumetric process loading, i.e. BOD applied (lb./day) per 1,000 cu. ft. As has been shown in Figure 2 the process loading factor defines the percentage of the substrate removed which will accumulate thereby defining the type of activated sludge process. The volumetric process loading on the other hand is directly proportional to the accumulation. For constant volumetric loading, the system starts with a high process loading factor. If the active solids are allowed to increase, the process loading factor continues to decrease causing the system to pass through the operational range of several modifications.

Sludge Wasting in Extended Aeration

The accumulation in an extended aeration system is mostly "Ash". Since, even at equilibrium this buildup amounts to 10 percent of the

metabolized organics, on a continuous operation there must be some sludge wasting. This wasting may be into the effluent as a result of denitrification, bulking, or aged sludge. If large amounts of sludge are wasted, sufficient active mass is lost to stimulate synthesis in an effort to return to equilibrium.

There is some room for disagreement as to the advisability of designing for sludge holding. The Ohio Department of Health study reported that effluent solids from the extended aeration systems had deoxygenation rate constants in the order of 0.10 to 0.15. It can be calculated that only about 15% of the BOD_L is utilized in 5 days. Compare this with the 68% to 82% oxygen demand satisfied in 5 days of ordinary wastes with deoxygenation rate constant of 0.10 to 0.15, respectively and one can visualize the much smaller rate of oxygen utilization by effluent solids. There is a need for more published data on the effluent deoxygenation constants. Such data would give support for a clearer definition of design requirements for extended aeration plants.

Sludge Recirculation

As indicated earlier, sludge recirculation is practiced as a necessary part of any activated sludge process. The magnitude of the recirculation should be obtained from a consideration of the advantages and disadvantages of high recirculation rates. A high recirculation ratio promotes a more constant bacterial population and eliminates troublesome denitrification in the sedimentation tank. At the same time, the system's hydraulic loading increases with increased recirculation ratio which at higher values will produce poor

sedimentation. As a minimum, the recirculation pump capacity must be sufficient to provide for the removal of all the settled solids. A sludge recirculation ratio of 1.0 to 2.0 is usually adequate for extended aeration systems. Nevertheless, several manufacturers of package extended aeration plants design for sludge return ratio of 5.0.

Aeration

These aerobic biological processes must be supplied with a source of oxygen. The value of 0.5 mg/l is normally taken as the minimum dissolved oxygen required to maintain the biological floc in an aerobic state. Atmospheric oxygen is invariably used to supply this need. The amount of air required depends upon the loading. For this reason the requirements are normally stated per unit of load. Based upon a 5 percent oxygen transfer efficiency extended aeration system requirements usually range from 1,700 to 2,000 cubic feet of air at atmospheric pressure per lb. of BOD applied.

The rate at which air is supplied varies with the plant classification. Homogeneous reactors utilize a fairly constant supply of air. Whereas, heterogenous reactors and those receiving large fluctuations in load have a variable air demand. The minimum aeration rate is sometimes determined by the air associated with the minimum mixing velocity in the reactor. For diffused aeration, this value is in the order of 2-3 cubic feet/min./ft.

Appendix

Symbols

A = Daily volatile sludge accumulation rate - wt/(vol-day)

A' = Gross synthesis resulting from assimilation of organic substrate within an aeration period - wt/time

A_a = Daily active mass accumulation rate - wt/(vol-day)

C = Yield coefficient or the fraction of food assimilated into organisms - wt/wt

F_A = Organic substrate applied per day - wt/day

F_R = Organic substrate removed per day - wt/day

j = Fraction of the active mass that, as a result of endogenous metabolism, becomes inert volatile solids

k = Endogenous metabolism rate - wt/(wt-day) or wt/(wt-time)

L = Volumetric process removal - wt/(vol-day)

M = Concentration of volatile solids (MLVS) - wt/vol

M_a = Concentration of active mass - wt/vol

M_a' = Active mass - wt

M_e = Concentration of volatile solids in the effluent - wt/vol

M_{ea} = Concentration of active mass in the effluent - wt/vol

Q = Flow rate - vol/day

t = Time

T_D = Aeration period - time